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# Updated CPUE of shortfin mako, *Isurus oxyrinchus*, caught by Japanese shallow-set longliner in the North Pacific[1]

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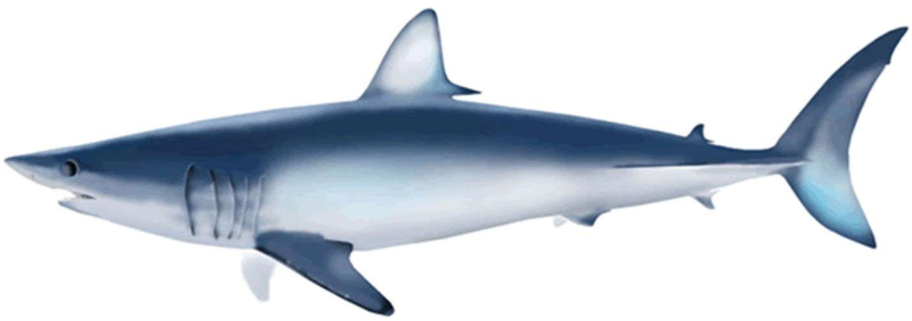

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**Abstract**

This working paper provides with the estimation of catch per unit of effort (CPUE) of shortfin mako, *Isurus oxyrinchus*, caught by Japanese shallow-set longliner during 1994 to 2016 in the western and central North Pacific. Two filtering methods as used in the previous analyses were applied to choose the reliable vessels using the data in 2000s. Filtering (I) is conducted based on the AIC estimated from CPUE standardization, in comparison between longline research vessel and commercial vessel. Filtering (II) is conducted based on the visual observations of the positive catch of shortfin mako for each vessel. Zero-inflated Nagative binomial model was used as the best model to standardize the CPUE for the filtered data. The yearly changes in the standardized CPUE suggested that the historical population trend of shortfin mako had slightly increased since 1990s until 2004, and then those had further increased since 2005 until 2016. These were mainly caused by the historical continuous decrease of the fishing effort with a slight decrease level of catch in the central and western North Pacific.

**Introduction**

Previous working paper presented the abundance indices of shortfin mako, *Isurus oxyrinchus*, caught by Japanese shallow-set longline fisheries during 1994 and 2013 using two filtering methods (Kai *et al*. 2015). The two filtering methods were applied to choose the reliable vessels using the data in 2000s. Filtering (I) was conducted based on the AIC estimated from CPUE standardization, in comparison between longline research vessel and commercial vessel. Filtering (II) was conducted based on the visual observations of the positive catch of shortfin mako for each vessel. The fishery area was separated into four areas using GLM tree (Ichinokawa and Brodziak 2010). Negative binomial model was used to standardize the CPUE for the filtered data from 1994 to 2013. In the previous ISC shark working group (WG) meeting in 2015, the WG noted that the increase in CPUE from 1994 to present is particularly high and unlikely given the low productivity of shortfin makos (ISC 2015). Then, WG pointed out some effects such as area, quarter, and targeting shift, and authors examined the impacts on the results. However, there was no apparent effect based on the change in targeting, at least based on the factors explored (ISC 2015). The WG therefore recommended that work continue improving the index for this fishery to help identify the reason for the trend that seems inconsistent with the productivity of the shark (ISC 2015).

Recently, Kai et al. (2017a, b) developed a length aggregated and disaggregated spatio-temporal delta-generalized linear mixed model (GLMM) and apply the method to fishery-dependent catch rates of shortfin mako sharks in the western and central North Pacific. The spatio-temporal model may provide an improvement over conventional time-series and spatially stratified models by yielding more precise and biologically interpretable estimates of abundance (Shelton et al. 2014; Thorson et al. 2015). The results of the analyses suggested that there has been a recent increasing trend in stock abundance since 2008 (Kai et al. 2017a). Although the spatio-temporal model improved the time series of catch rates and the unrealistic increase of the catch rates was disappeared, one issue is the shorter period of the analyses between 2006 and 2014. Then we need to develop the spatio-temporal model to apply it to the whole data from 1994 to 2016 in future work. As the first step, we update the abundance indices during 1994 and 2016 using the same filtering methods and area-stratification as the previous analyses (Kai et al. 2015) to compare with those predicted by the spatio-temporal model.

## Materials and Methods

*Data sources*

Set-by-set logbook data from Japanese offshore and distant water longline fishery are used to estimate the standardized CPUE over the period 1994-2016. Set-by-set data used in this study included information on catch number, amount of effort (number of hooks), number of branch lines between floats (hooks per basket: HPB) as a proxy for gear configuration, location (longitude and latitude) of set by resolution of 1 × 1 degree square, vessel identity, fishery type (offshore or distant water), and the prefecture in Japan where the longline boats were registered. The offshore-water fleet was defined by tonnage of vessels between 20 and 120 MT, while the distant-water fleet consisted of vessels larger than 120 MT.

*Data filtering*

Filtering was used for the logbook data to remove the mis-reporting data. The vessels were selected by the size (20~150 vessel tonnage) and the registered prefectures ("Tohoku and Hokkaido") because these fishery frequently target blue shark (*Prionace glauca*) and shortfin mako is frequently caught as bycatch. The data was also chosen by the number of hooks per baskets (HPB; 3~5) to select a shallow-set fishery. In addition, we conducted two additional filtering to remove the data of cruise which had apparently discarded the shortfin mako shark. Filtering (I): similar trends of CPUE to those estimated from the longline research vessel by Ohshimo *et al*. (2014) were selected. We used the delta lognormal model with the filtered data for the same periods (April to June for 2000, 2002-2013), area (25-40° N, 140-150° E), and depth (3-5 HPB) to compare with the CPUE of the research data (Oshimo *et al*. 2014). Filtering (II): The data of 19 vessels were selected from 28 vessels based on the visual observation of CPUE pattern of each set of shortfin mako in the past. The details of the filtering methods are described in the previous working paper (Kai *et al*. 2015). We choose the same data of the logline fleets for the filtering (I) and (II) to maintain the consistency with the previous analysis.

*CPUE standardization*

Standardized CPUE for 1994-2016 was estimated using the generalized linear model (GLM) with logbook data. We used the same area stratifications and same model as those used in the previous analyses (Kai et al. 2015):

$$\text{Log (Catch)} = \text{Intercept} + \alpha_1\text{Year} + \alpha_2\text{Quarter} + \alpha_3\text{Area} + \alpha_4\text{Fishery} + \alpha_5\ \text{Quarter} * \text{Area} + \text{offset (log (hook)), Catch} \sim \text{NB} \tag{1}$$

"Catch" is the response variable and is a positive captured number of shortfin mako, "Effort" is number of hooks (×1000) given as an offset term, $\alpha i$ are coefficients of each explanatory variables, "Year" is a year effect from 1994 to 2016, "Quarter" is a seasonal effect in Q1(Jan-Mar), Q2(Apr-Jun), Q3(Jul-Sep), and Q4(Oct- Dec), "Area" is a horizontal spatial effect (Area 1 – 4, see at Fig. 2), "Fishery type" is a two types of fishery effects (offshore or distant water). These are categorical explanatory variables. In the previous analyses, we used three interaction terms (Year*Area, Year*Quarter, and Quarter*Area). However, we used only one interaction term due to a lack of data. We sequentially removed the explanatory variables to examine the impacts of the main explanatory variables on the fitting to the data without overfitting using the AIC (Akaike 1973) and BIC (Schwarz, 1978). The full model was selected as the best model (Table 2). However, the residual pattern of the negative binomial model (NB) was not normally distributed and the frequency distribution of shortfin mako catch per operation showed high zero-catch and dispersion ratio (Fig. 1), so that we also used zero-inflated Poisson (ZIP) and zero-inflated negative binomial model (ZINB) (Zuur et al. 2009), and model selection was conducted based on the AIC and BIC. The best model was selected from the full model of each model (Table 2). For the best model, lower and upper 95 % confidence intervals (CI) of the yearly changes in the relative CPUE and its *CV* were estimated using the bootstrap with one thousand nonparametric replicates (Efron and Tibshirani 1994). These standardized CPUEs were compared with nominal CPUEs of shortfin mako. Histograms of Pearson residuals for CPUE values under the three models were drawn to check the goodness of fit at each observation. In addition, histograms of Pearson residuals for CPUE values against each explanatory variable were plotted for the selected best model. All computations were performed in R version 3.3.2 for Windows (R Development Core Team 2016). The negative binomial and zero-inflated models were computed with the "MASS" and "pscl" libraries of R respectively.

*Sensitivity runs*

Four sensitivity runs were conducted to examine the impacts of (i) operational changes due to the damage of the main fishing ports by Tsunami in 2011, (ii) data filtering, (iii) SST, and (iv) target effect between blue sharks and swordfish on the yearly changes in standardized CPUE. "SST" represents a habitat temperature preference and a quadratic equation was used as an indicator of habitat preference. The SST variable is a continuous explanatory variable and the others are categorical explanatory variables. The 10th percentile of the swordfish CPUE values was incorporated to reduce the influence of the target behavior on the CPUE (Hiraoka et al. 2016). Japanese shallow-set longline fishery largely changes the annual target species seasonally and geographically from swordfish to blue shark, especially occurred in spring (Hiraoka et al. 2016).

## Results

*Patterns of the operation and catch*

Operational locations of Japanese shallow-set longliner in the North Pacific and the positive catches showed that shortfin mako sharks were dominantly caught in the western North Pacific (Fig.2). Area-2 accounted for 58.3 % catch of all areas, area-3 accounted for 18.2 %, and area-4 accounted for 15.6 % and area-1 was less than 10 % (7.9%). Spatiotemporal changes in catch number of shortfin mako indicated that the fishermen changed latitudinally the operational area from southern area to the northern area corresponding with the seasonal changes from spring-summer to autumn-winter (Fig. 3). The wide longitudinal operational pattern was observed in the western and central North Pacific throughout the year. However, the hotspots of coastal and offshore area (140-150° E) were remarkable in spring and summer, while the hotspots of distant-water area (170-180° E) were remarkable in autumn and winter.

Catch number (before filtering?) of shortfin mako increased in 1990s and 2000s and reached to 13,904 number in 2009, after that the trends had slightly decreased (Fig 4 and Table 1). Fishing effort (number of hooks) had continuously decreased since 1994 and decreased 18% in 2016. Nominal CPUE had slightly increased since 1994 to 2016 except in 2013. The positive catch ratio (or reporting ratio) of shortfin mako (number of sets with shortfin mako recorded / total number of sets) had slightly increased since 1994 and fluctuated from 70.1 % to 91.0 % in recent 5 years. Catch number of shortfin mako fluctuated largely by year and season but the annual trends in nominal CPUE showed a similar increase trends to the season-aggregated catch number (Fig. 5). Catch number and number of hooks in area-2 were almost dominant throughout the years and nominal CPUE had been highest since 2009 except in 2016 (Fig. 6). Catch number and number of hooks for offshore fishery were always higher than those for distant-water fishery throughout the years but the yearly changes in the nominal CPUE were almost same between them (Fig. 7).

*Selection of the best model and the diagnostics*

Three models were reasonably converged and ZINB model was selected as the most parsimonious model from the comparisons among AIC and BIC (Table 2). The yearly changes in standardized CPUE of three models showed similar increasing trends throughout the years (Fig. 8). The 95% confidence intervals (CI) of the best fitted model showed that the ranges were narrow during 1994 to 2010, and the ranges after 2010 were wide. Histograms of Pearson residuals for CPUE values showed that the residual of NB was extremely skewed to the negative values, while the residuals of zero-inflated models were almost normal distribution with a small negative bias (Fig. 9). Q-Q plot supported the results of the residual distribution, however, the boxplots of Pearson residuals for the best fitted ZINB showed that small negative biases for all the explanatory variables (Fig. 10). The CPUEs in area-2 were higher than a mean value of CPUE irrespective of the season (Fig. 11). The CPUEs in area-4 were higher than a mean value of CPUE except for quarter 1. The CPUEs in area-1 were lower than a mean value of CPUE for all seasons. The CPUEs in area 3 were lower than a mean value of CPUE except for quarter 1.

*Sensitivity analyses*

The results of sensitivity to target effect indicated that the target changes between two target species had a small impact on the annual trends in the CPUE of shortfin mako (Fig. 12). Since shortfin mako shark is bycatch species unlike the swordfish and blue shark, the target shifts may not largely influence on the trends in the CPUE. The results of sensitivity to the effect of SST indicated that there was small impact of the SST on the yearly changes in the CPUE (Fig. 13). Probably, SST is changeable by seasons and areas and these effects were sufficiently considered in the full model by the interaction term. Separation of one time series into two periods showed a remarkable increase of CPUE before 2011 and slight increase of the CPUE after 2010 (Fig. 14). For the most recent stock assessment of North Pacific blue shark (ISC 2017), we used a continuous time series for the standardized CPUE of blue shark caught by Japanese shallow-set longliner because it was very difficult to detect the effect of the change in the fishing port in 2011 on the standardized CPUE. The maps of the year and season specific catch locations (Figs. 16-18) as well as operational areas (Figs. 19-21) showed that there were no clear spatio-temporal operational patterns of catch and effort before and after the Tsunami in 2011.

**Discussions**

This document paper estimated a historical population trend of shortfin mako in the North Pacific using generalized linear model with sufficient spatial-temporal fishery data caught by Japanese shallow-set longline fishery from 1994 to 2016 in the central and western North Pacific. The yearly changes in the standardized CPUE suggested that the historical population trend of shortfin mako had slightly increased since 1990s until 2004 (2.03 times and corresponding to $r = 0.071$), and then those had further increased since 2005 until 2016 (2.78 times and corresponding to $r = 0.085$). These were mainly caused by the continuous historical decrease of the fishing effort with a slight decrease level of catch in the central and western North Pacific (Fig. 4). Although, shortfin mako shark is known to be vulnerable to high pressure of fisheries because of a low productivity due to slow growth, late maturity, and low fecundity (Semba et al. 2009, 2011), these growth rates of the population are likely to be plausible because the latest study of the population growth rates ($r$) of shortfin mako estimated from the two-stage sex model showed a similar or higher values (Yokoi et al. 2017). In addition, the observation errors of estimated standardized CPUE resulted in the fluctuation of the values (Fig. 8).

The World Conservation Union (IUCN) currently lists the shortfin mako as “Near Threatened” due to a lack of evidence that population levels have been sufficiently depleted to warrant listing it as “Vulnerable” (Cailliet et al. 2013). In the North Pacific, stock status of the shortfin mako is poorly known because a full stock assessment for shortfin mako has not been conducted yet. However, some aspects of the information had documented in the North Pacific. Population dynamics of shortfin mako in the Northwest Pacific were estimated using demographic model and the number was found to be dropping under current conditions (Tsai et al. 2014). Additionally, it was shown that the annual spawning potential ratio (SPR) was lower than the SPR35% and had a decreasing trend since 2000 (Chang and Liu 2009). These results might be the reflection of the partial stock status in the North Pacific but the spatial coverage may be insufficient to judge the entire stock status, and large uncertainties are included in terms of the biological parameters in those assessments. Further, standardized catch rate based on the onboard observers in the western and central Pacific Ocean showed significant declining trends by 7% per year but the performance of the standardized model was poor and the results were less reliable (Clarke et al. 2013). As we mentioned above, recent developed length-disaggregated spatio-temporal model revealed that size specific catch rates provide an indication that there has been a recent increasing trend since 2008 (Kai et al. 2017a). The results of same period were consistent with those of our results.

Two-step filtering had a large impact on the absolute estimates of standardized CPUE, while the slight increasing trends in the standardized CPUE over the years were almost similar among with and without the filtering (Fig. 15). The accuracy of the absolute estimates is more important than the relative estimates because the catch number of shortfin mako shark will be estimated through the multiplication by the total fishing effort. However, the current filtering methods have a few issues: (1) the spatial-temporal coverage of the survey data used for the validation of the CPUE trends is limited to small area (25-40 ˚N and 140-150 ˚E) and shorter periods (2000-2014) with one season (May-July), (2) the selection of the vessels based on the visual observation of CPUE pattern of each set of shortfin mako shark is subjective. It may be difficult to solve these issues in future and these filtering might lose the correct data. Further, the impacts of the 2-step filtering is small. These facts indicates that 2-step filtering may not be necessary in future analysis. Rather, we should improve the accuracy of the estimate using the spatio-temporal model with the data over 1994-2016 in future work.

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Tables

Table 1. Number of efforts, number of shortfin mako shark in catch, and positive catch ratios for shallow-set data with and without 2 stage filtering.

| | All shallow-set | | | 1st filtering | | | 2nd filtering | | |
|---|---|---|---|---|---|---|---|---|---|
| Year | No of effort (Million hooks) | No of catch (number) | Ratio of possitive catch (%) | No of effort (Million hooks) | No of catch (number) | Ratio of possitive catch (%) | No of effort (Million hooks) | No of catch (number) | Ratio of possitive catch (%) |
| 1994 | 23.95 | 3,047 | 18.6 | 8.13 | 1,653 | 26.3 | 4.43 | 1,512 | 47.6 |
| 1995 | 21.96 | 3,425 | 22.6 | 8.87 | 2,271 | 31.8 | 4.63 | 1,915 | 51.7 |
| 1996 | 20.01 | 4,813 | 30.2 | 8.95 | 3,126 | 39.7 | 5.23 | 2,490 | 50.8 |
| 1997 | 19.64 | 6,366 | 34.0 | 8.75 | 3,599 | 41.8 | 5.53 | 2,754 | 47.8 |
| 1998 | 20.21 | 6,837 | 38.8 | 9.71 | 3,991 | 43.4 | 6.37 | 3,244 | 51.2 |
| 1999 | 20.41 | 8,584 | 44.1 | 10.60 | 5,464 | 52.6 | 6.74 | 4,115 | 59.8 |
| 2000 | 23.13 | 11,697 | 47.1 | 12.86 | 8,080 | 56.7 | 7.64 | 5,806 | 66.1 |
| 2001 | 23.26 | 10,494 | 47.7 | 11.83 | 6,267 | 53.7 | 6.71 | 3,976 | 57.7 |
| 2002 | 21.27 | 8,787 | 46.3 | 10.86 | 4,987 | 50.2 | 6.65 | 3,365 | 53.9 |
| 2003 | 19.14 | 9,504 | 45.3 | 9.58 | 5,907 | 51.8 | 5.75 | 3,946 | 55.4 |
| 2004 | 19.14 | 9,803 | 47.2 | 9.98 | 5,401 | 48.9 | 5.57 | 3,791 | 59.3 |
| 2005 | 17.35 | 12,198 | 55.0 | 8.65 | 6,202 | 53.8 | 4.69 | 4,559 | 66.1 |
| 2006 | 16.06 | 11,602 | 58.8 | 8.53 | 6,642 | 58.8 | 4.18 | 4,955 | 77.0 |
| 2007 | 18.48 | 14,219 | 59.5 | 10.30 | 9,070 | 56.8 | 5.55 | 6,605 | 73.8 |
| 2008 | 16.48 | 11,553 | 64.1 | 8.62 | 7,102 | 63.4 | 4.61 | 4,968 | 78.3 |
| 2009 | 14.68 | 13,904 | 64.8 | 7.92 | 9,919 | 67.3 | 3.86 | 5,543 | 72.9 |
| 2010 | 13.59 | 11,873 | 65.3 | 6.75 | 7,899 | 71.3 | 2.93 | 3,575 | 76.0 |
| 2011 | 7.62 | 8,475 | 76.2 | 3.72 | 4,830 | 81.6 | 1.79 | 2,433 | 82.1 |
| 2012 | 9.35 | 10,561 | 70.1 | 4.57 | 5,869 | 78.5 | 1.84 | 2,643 | 82.6 |
| 2013 | 9.79 | 7,793 | 67.8 | 4.51 | 4,208 | 75.2 | 1.73 | 1,884 | 81.2 |
| 2014 | 9.67 | 11,521 | 75.5 | 3.98 | 4,953 | 76.6 | 1.15 | 1,484 | 77.2 |
| 2015 | 7.76 | 11,231 | 75.3 | 2.84 | 4,571 | 75.1 | 1.36 | 1,866 | 68.5 |
| 2016 | 4.31 | 7,690 | 91.0 | 1.46 | 3,252 | 91.1 | 1.09 | 2,080 | 89.7 |

Table 2. Model structure and changes in AIC and BIC among different model structure. Δ denotes a difference between the value of criteria and the minimum value.

| Model (explanatory variables) | AIC | ΔAIC | BIC | ΔBIC |
|---|---|---|---|---|
| Negative binomial | | | | |
| Null | 123,275 | 5,758 | 123,291 | 5,195 |
| Year | 120,926 | 3,410 | 121,125 | 3,029 |
| Year + Quarter | 120,892 | 3,376 | 121,116 | 3,020 |
| Year + Quarter + Area | 119,297 | 1,781 | 119,546 | 1,450 |
| Year + Quarter + Area + Fishery | 119,419 | 1,903 | 119,684 | 1,588 |
| Year + Quarter + Area + Fishery + Quarter*Area | 118,393 | 876 | 118,724 | 628 |
| Zero-inflated poisson | | | | |
| Zero-inflation: Year + Quarter + Area + Fishery<br>Count: Year + Quarter + Area + Fishery + Quarter*Area | 148,955 | 31,439 | 149,527 | 31,431 |
| Zero-inflated Negative binomial | | | | |
| Zero-inflation: Year + Quarter + Area + Fishery<br>Count: Year + Quarter + Area + Fishery + Quarter*Area | 117,516 | 0 | 118,096 | 0 |

Table 3. Summaries of the yearly changes in nominal CPUE, standardized CPUE with 95 % confidence intervals, and its coefficient of variations (CV) for the full model.

| Year | Nominal CPUE | Standardized CPUE | Normalized Nominal CPUE | Normalized Standardized CPUE | Lower of 95 % CI | Upper of 95 % CI | CV (%) |
|---|---|---|---|---|---|---|---|
| 1994 | 0.34 | 0.31 | 0.36 | 0.36 | 0.33 | 0.41 | 6.27 |
| 1995 | 0.41 | 0.41 | 0.44 | 0.48 | 0.44 | 0.52 | 5.35 |
| 1996 | 0.48 | 0.42 | 0.51 | 0.49 | 0.45 | 0.53 | 5.41 |
| 1997 | 0.50 | 0.43 | 0.53 | 0.51 | 0.47 | 0.55 | 5.23 |
| 1998 | 0.51 | 0.43 | 0.54 | 0.51 | 0.47 | 0.54 | 4.92 |
| 1999 | 0.61 | 0.56 | 0.65 | 0.66 | 0.61 | 0.70 | 4.63 |
| 2000 | 0.76 | 0.57 | 0.81 | 0.67 | 0.63 | 0.72 | 4.43 |
| 2001 | 0.59 | 0.47 | 0.63 | 0.55 | 0.51 | 0.59 | 4.57 |
| 2002 | 0.51 | 0.43 | 0.54 | 0.50 | 0.47 | 0.54 | 4.77 |
| 2003 | 0.69 | 0.61 | 0.73 | 0.72 | 0.66 | 0.78 | 5.55 |
| 2004 | 0.68 | 0.58 | 0.73 | 0.69 | 0.64 | 0.75 | 5.02 |
| 2005 | 0.97 | 0.81 | 1.03 | 0.96 | 0.88 | 1.04 | 4.93 |
| 2006 | 1.19 | 1.00 | 1.26 | 1.18 | 1.09 | 1.27 | 5.00 |
| 2007 | 1.19 | 0.97 | 1.27 | 1.14 | 1.07 | 1.22 | 4.24 |
| 2008 | 1.08 | 0.85 | 1.15 | 1.00 | 0.94 | 1.07 | 4.53 |
| 2009 | 1.44 | 1.13 | 1.53 | 1.33 | 1.23 | 1.43 | 4.71 |
| 2010 | 1.22 | 1.01 | 1.30 | 1.19 | 1.11 | 1.28 | 4.71 |
| 2011 | 1.36 | 1.38 | 1.44 | 1.63 | 1.47 | 1.79 | 6.10 |
| 2012 | 1.43 | 1.29 | 1.53 | 1.53 | 1.38 | 1.69 | 6.12 |
| 2013 | 1.09 | 1.24 | 1.16 | 1.46 | 1.35 | 1.58 | 5.17 |
| 2014 | 1.29 | 1.39 | 1.37 | 1.64 | 1.43 | 1.86 | 7.81 |
| 2015 | 1.37 | 1.41 | 1.46 | 1.66 | 1.50 | 1.85 | 6.49 |
| 2016 | 1.90 | 1.81 | 2.03 | 2.13 | 1.93 | 2.34 | 6.28 |

Table 4. Summaries of the yearly changes in CPUE for sensitivity analyses.

| Year | Nominal | NB | ZINB | ZINB with Target | ZINB with SST | ZINB with Target and SST | ZINB with data before 2011 | ZINB with data after 2010 | ZINB without filtering | ZINB with 1st filtering |
|---|---|---|---|---|---|---|---|---|---|---|
| 1994 | 0.36 | 0.38 | 0.36 | 0.37 | 0.36 | 0.37 | 0.49 | NA | 0.21 | 0.28 |
| 1995 | 0.44 | 0.47 | 0.48 | 0.48 | 0.48 | 0.48 | 0.64 | NA | 0.26 | 0.34 |
| 1996 | 0.51 | 0.53 | 0.49 | 0.49 | 0.49 | 0.49 | 0.65 | NA | 0.38 | 0.45 |
| 1997 | 0.53 | 0.53 | 0.51 | 0.50 | 0.51 | 0.50 | 0.66 | NA | 0.52 | 0.54 |
| 1998 | 0.54 | 0.54 | 0.51 | 0.51 | 0.51 | 0.51 | 0.67 | NA | 0.55 | 0.51 |
| 1999 | 0.65 | 0.63 | 0.66 | 0.66 | 0.66 | 0.66 | 0.86 | NA | 0.65 | 0.62 |
| 2000 | 0.81 | 0.68 | 0.67 | 0.68 | 0.67 | 0.68 | 0.89 | NA | 0.66 | 0.65 |
| 2001 | 0.63 | 0.57 | 0.55 | 0.55 | 0.55 | 0.55 | 0.73 | NA | 0.62 | 0.58 |
| 2002 | 0.54 | 0.53 | 0.50 | 0.50 | 0.50 | 0.50 | 0.67 | NA | 0.63 | 0.56 |
| 2003 | 0.73 | 0.73 | 0.72 | 0.72 | 0.72 | 0.72 | 0.95 | NA | 0.77 | 0.77 |
| 2004 | 0.73 | 0.71 | 0.69 | 0.69 | 0.69 | 0.69 | 0.91 | NA | 0.76 | 0.63 |
| 2005 | 1.03 | 1.00 | 0.96 | 0.96 | 0.96 | 0.96 | 1.27 | NA | 1.00 | 0.84 |
| 2006 | 1.26 | 1.13 | 1.18 | 1.17 | 1.18 | 1.17 | 1.54 | NA | 1.03 | 0.89 |
| 2007 | 1.27 | 1.15 | 1.14 | 1.13 | 1.14 | 1.13 | 1.49 | NA | 1.09 | 1.01 |
| 2008 | 1.15 | 1.00 | 1.00 | 0.99 | 1.00 | 0.99 | 1.30 | NA | 0.94 | 0.91 |
| 2009 | 1.53 | 1.35 | 1.33 | 1.33 | 1.33 | 1.33 | 1.73 | NA | 1.34 | 1.41 |
| 2010 | 1.30 | 1.18 | 1.19 | 1.19 | 1.19 | 1.19 | 1.56 | NA | 1.32 | 1.42 |
| 2011 | 1.44 | 1.73 | 1.63 | 1.63 | 1.63 | 1.63 | NA | 0.90 | 1.60 | 1.65 |
| 2012 | 1.53 | 1.52 | 1.53 | 1.54 | 1.53 | 1.54 | NA | 1.00 | 1.45 | 1.46 |
| 2013 | 1.16 | 1.48 | 1.46 | 1.47 | 1.47 | 1.47 | NA | 0.84 | 1.27 | 1.35 |
| 2014 | 1.37 | 1.60 | 1.64 | 1.66 | 1.64 | 1.66 | NA | 1.04 | 1.86 | 1.75 |
| 2015 | 1.46 | 1.54 | 1.66 | 1.66 | 1.66 | 1.66 | NA | 1.09 | 1.89 | 1.84 |
| 2016 | 2.03 | 2.02 | 2.13 | 2.12 | 2.13 | 2.12 | NA | 1.13 | 2.22 | 2.53 |

Figures

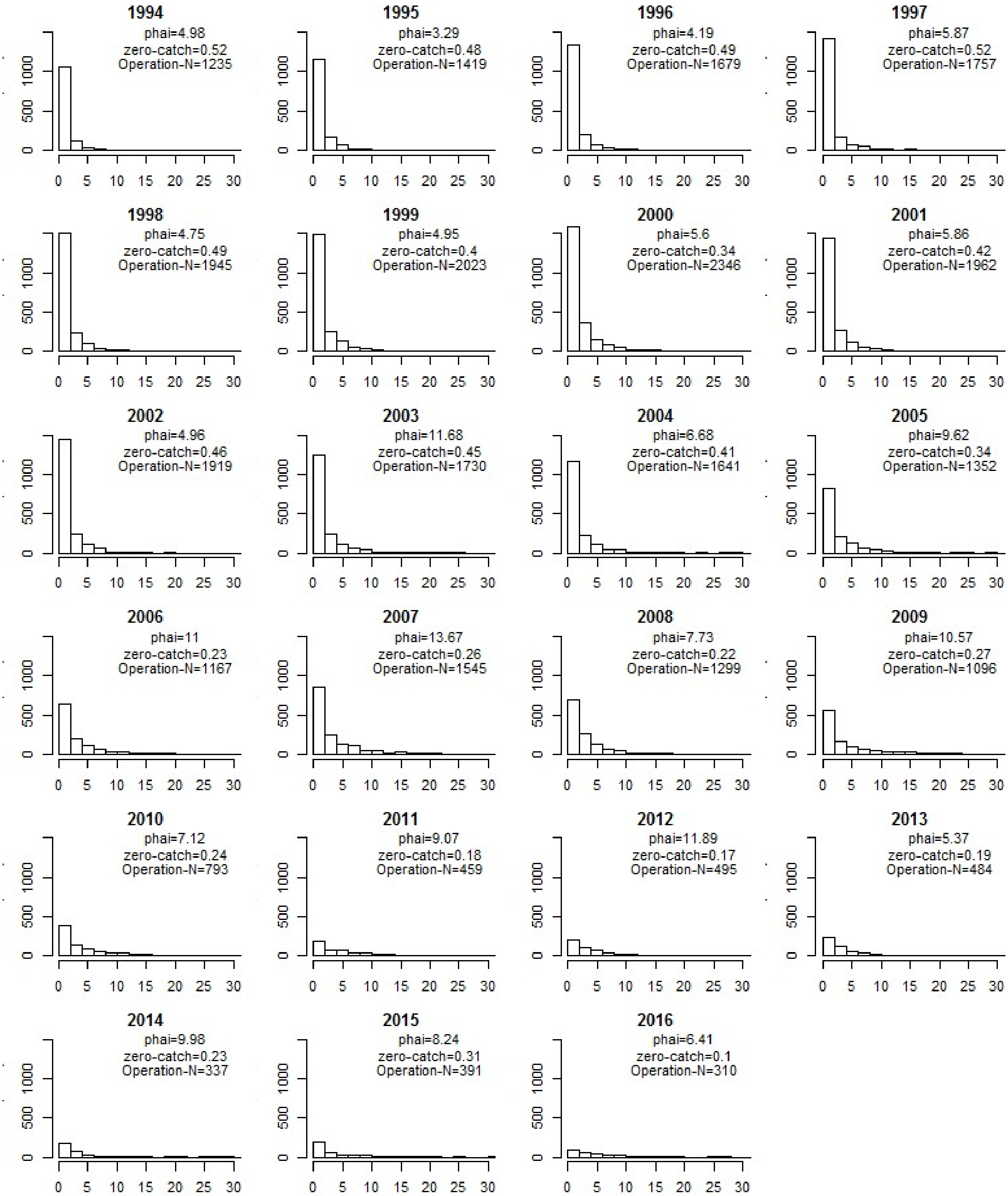


Fig.1 Frequency distribution (Number) of shortfin mako catch per operation from 1994 to 2016 after 2-step filtering. "Phai" denotes the dispersion ratio (mean/variance), "zero-catch" denotes the ratio of zero catch, and "Operation-N" denotes the total number of operation (thousands).

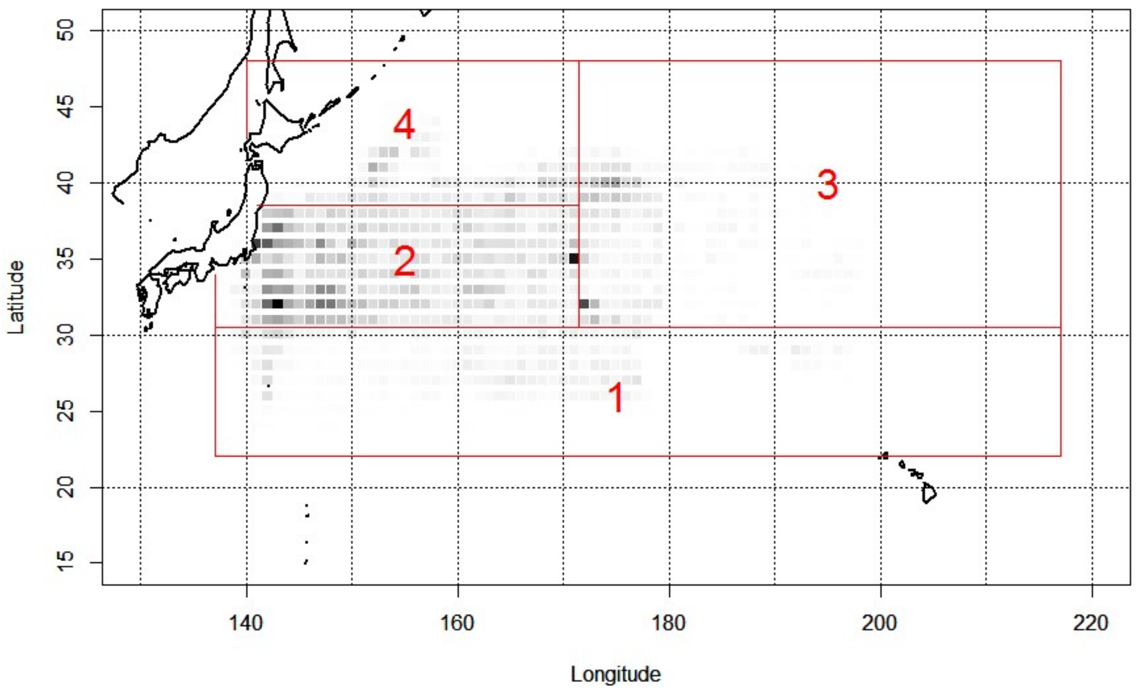


Fig. 2 Catch location of shortfin mako shark in the North pacific from 1994 to 2016, and area stratification for CPUE standardization. Darker square denotes the higher catch at the location.

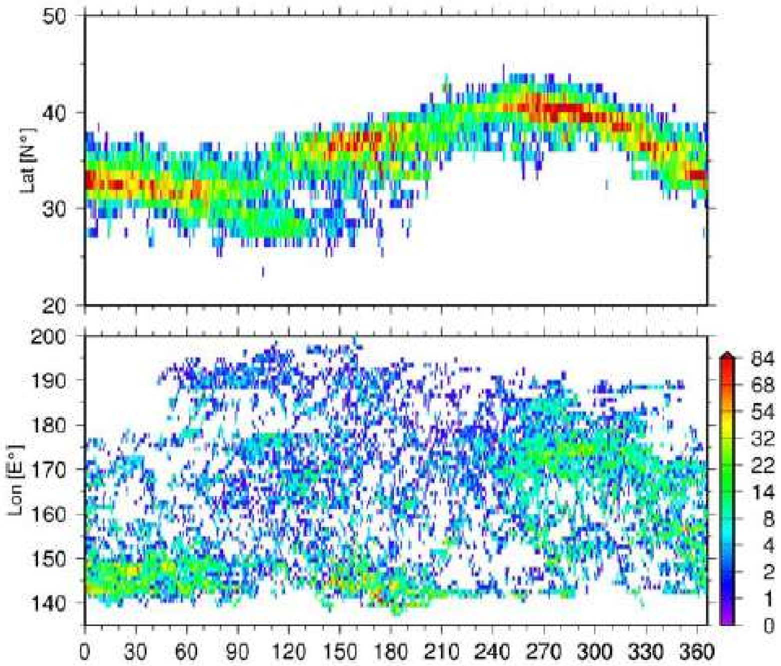

Fig. 3 Spatiotemporal change of catch number (color scale). X-axis is the serial date within a year. Y-axis of upper and lower figure represents latitude and longitude, respectively. Color reflects the number of catch (Referred to fig.2 in Shiozaki et al. 2013).

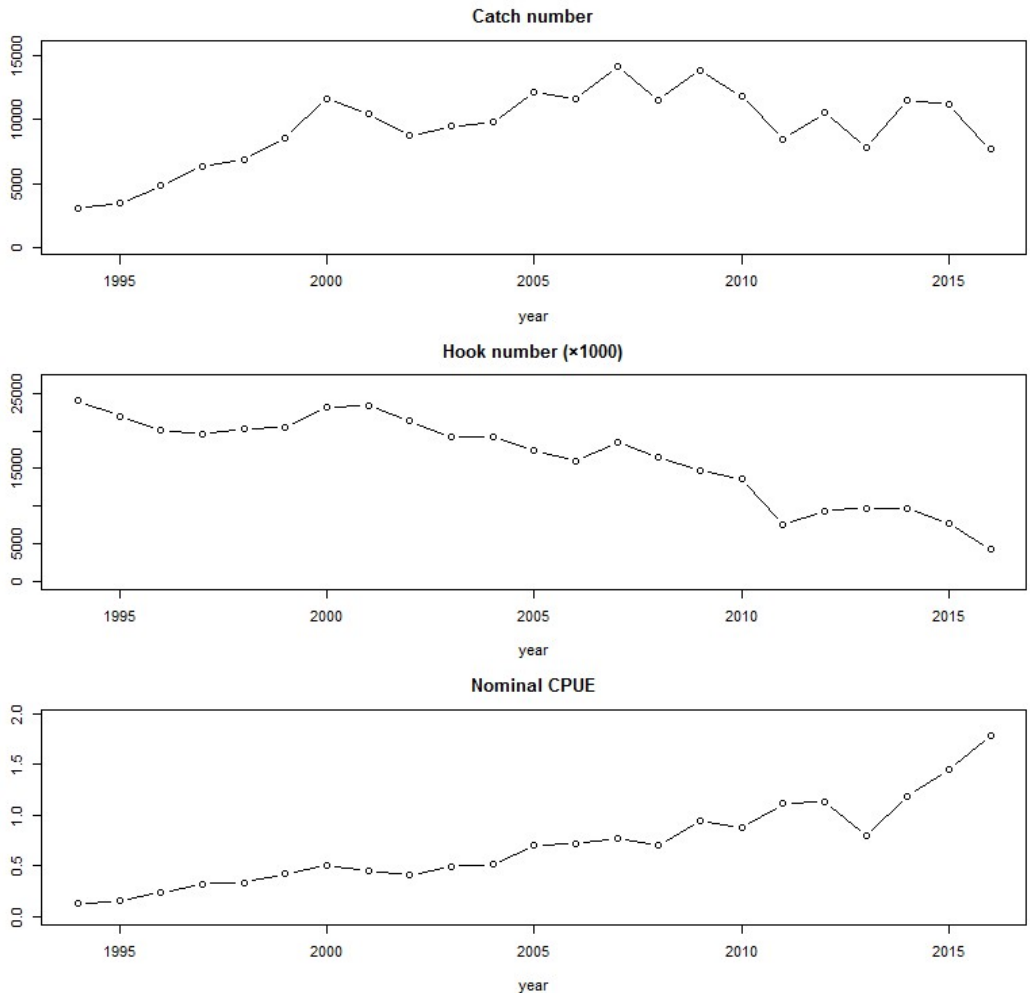


Fig. 4 Yearly changes in number of catch for shortfin mako (upper figure), number of total hooks (millions) (middle figure), and nominal CPUE (per 1000 hooks) (lower figure) for data without 2 step filtering.

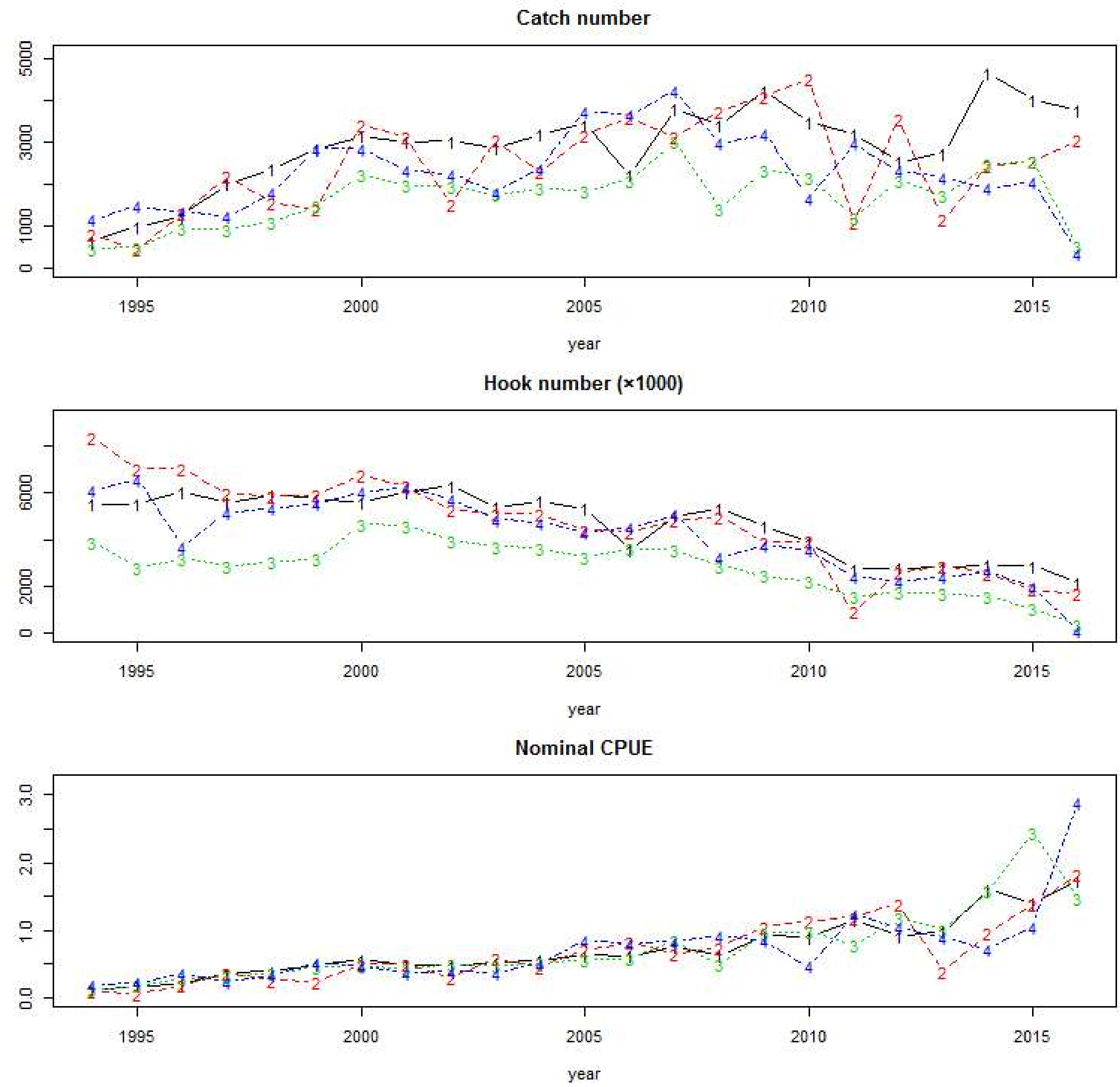


Fig. 5 Year and season specific changes in number of catch for shortfin mako (upper figure), number of total hooks (millions) (middle figure), and nominal CPUE (per 1000 hooks) (lower figure) for data without 2 step filtering.

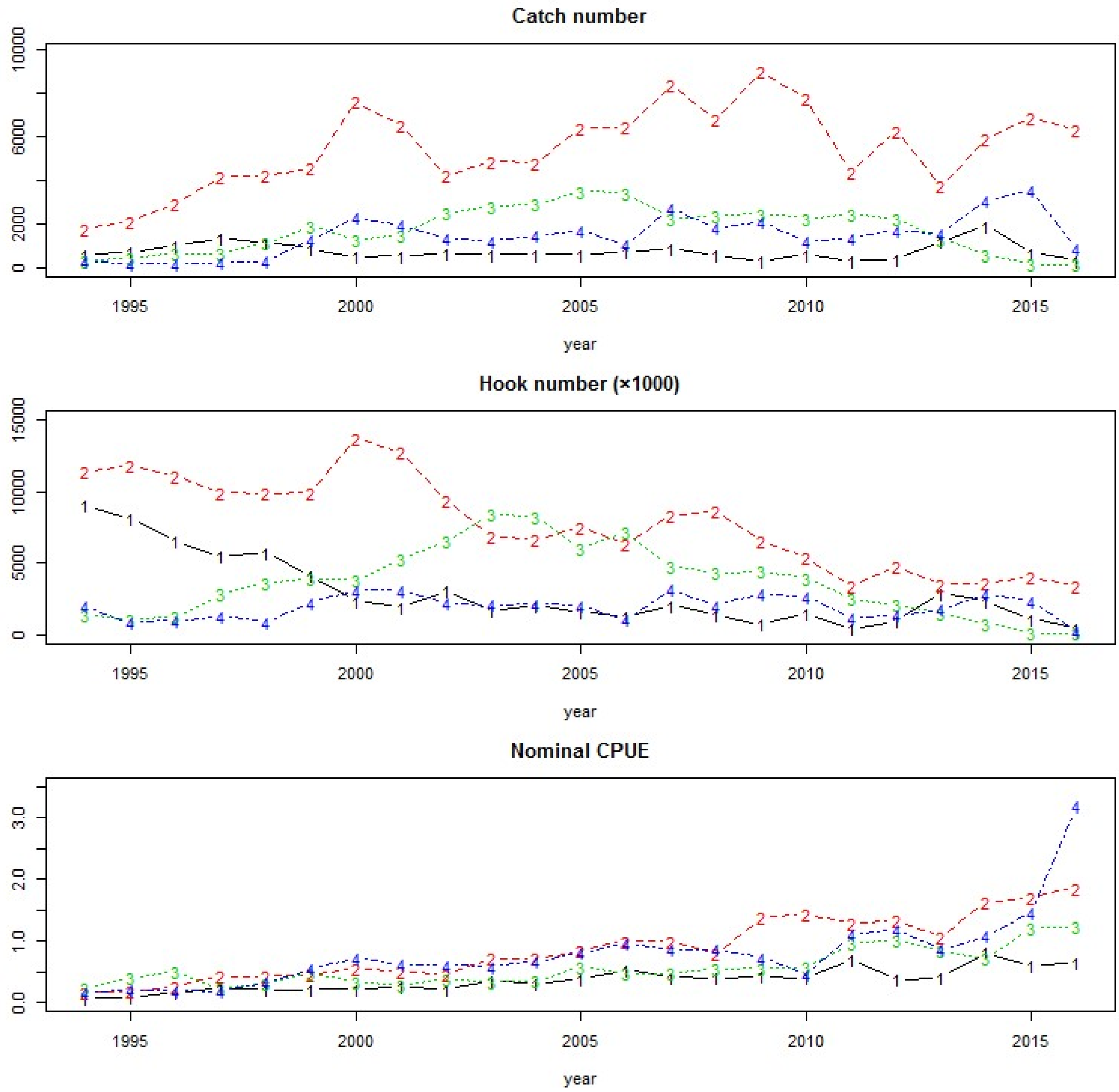


Fig. 6 Year and area specific changes in number of catch for shortfin mako (upper figure), number of total hooks (millions) (middle figure), and nominal CPUE (per 1000 hooks) (lower figure) for data without 2 step filtering.

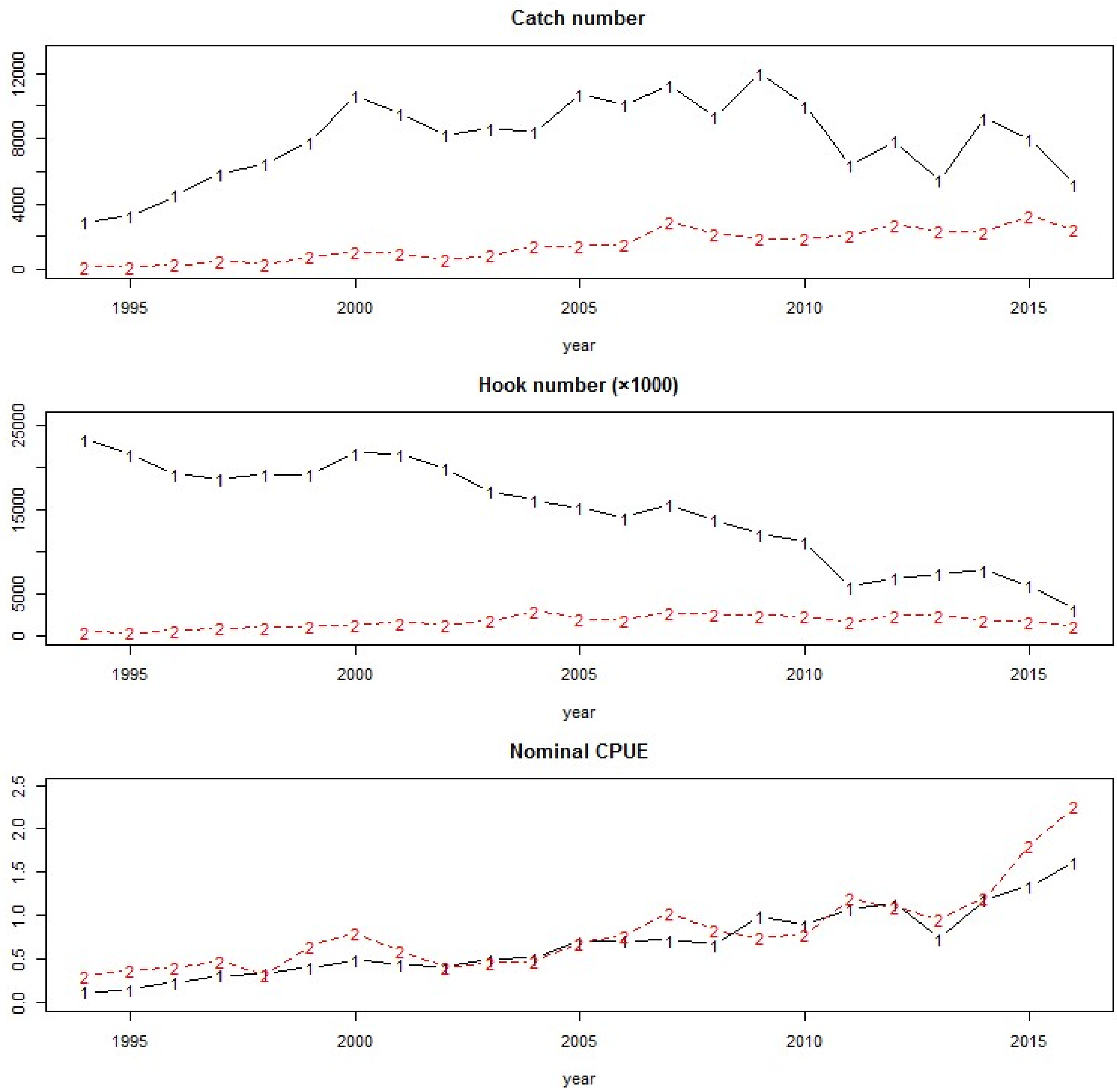


Fig. 7 Year and fishery specific changes in number of catch for shortfin mako (upper figure), number of total hooks (millions) (middle figure), and nominal CPUE (per 1000 hooks) (lower figure) for data without 2 step filtering.

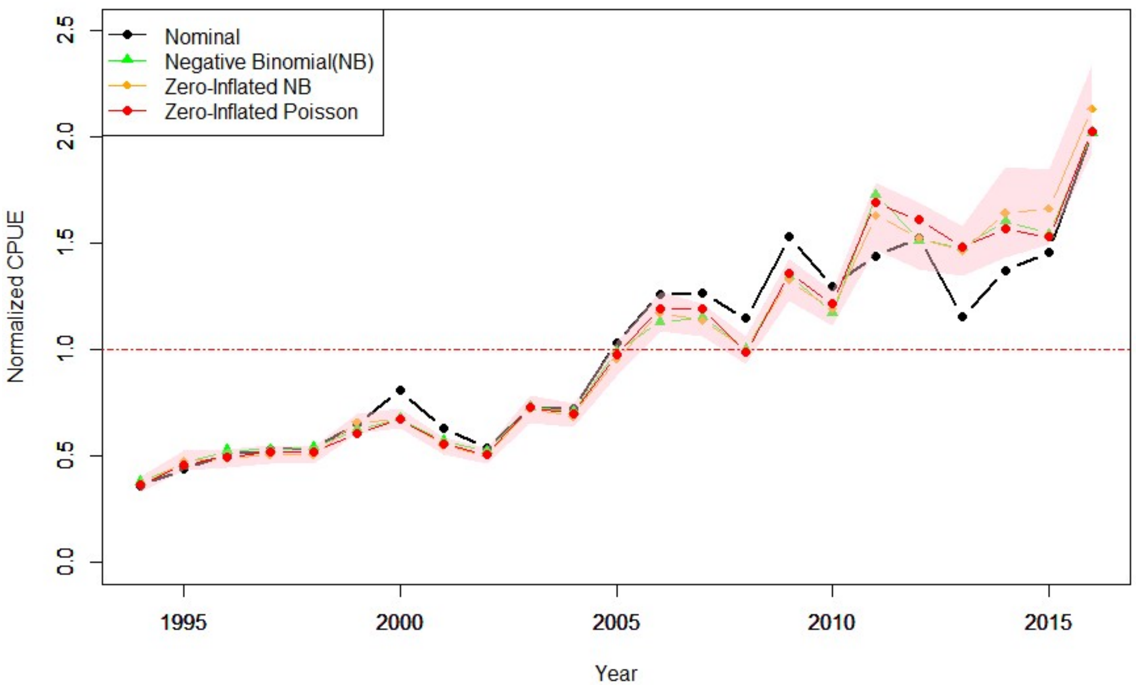


Fig. 8. Yearly changes in nominal CPUE and standardized CPUEs (least squares means) for shortfin mako estimated from three models (NB: Negative Binomial, ZIP: Zero-Inflated Poisson, and ZINB: Zero-Inflated Negative Binomial).

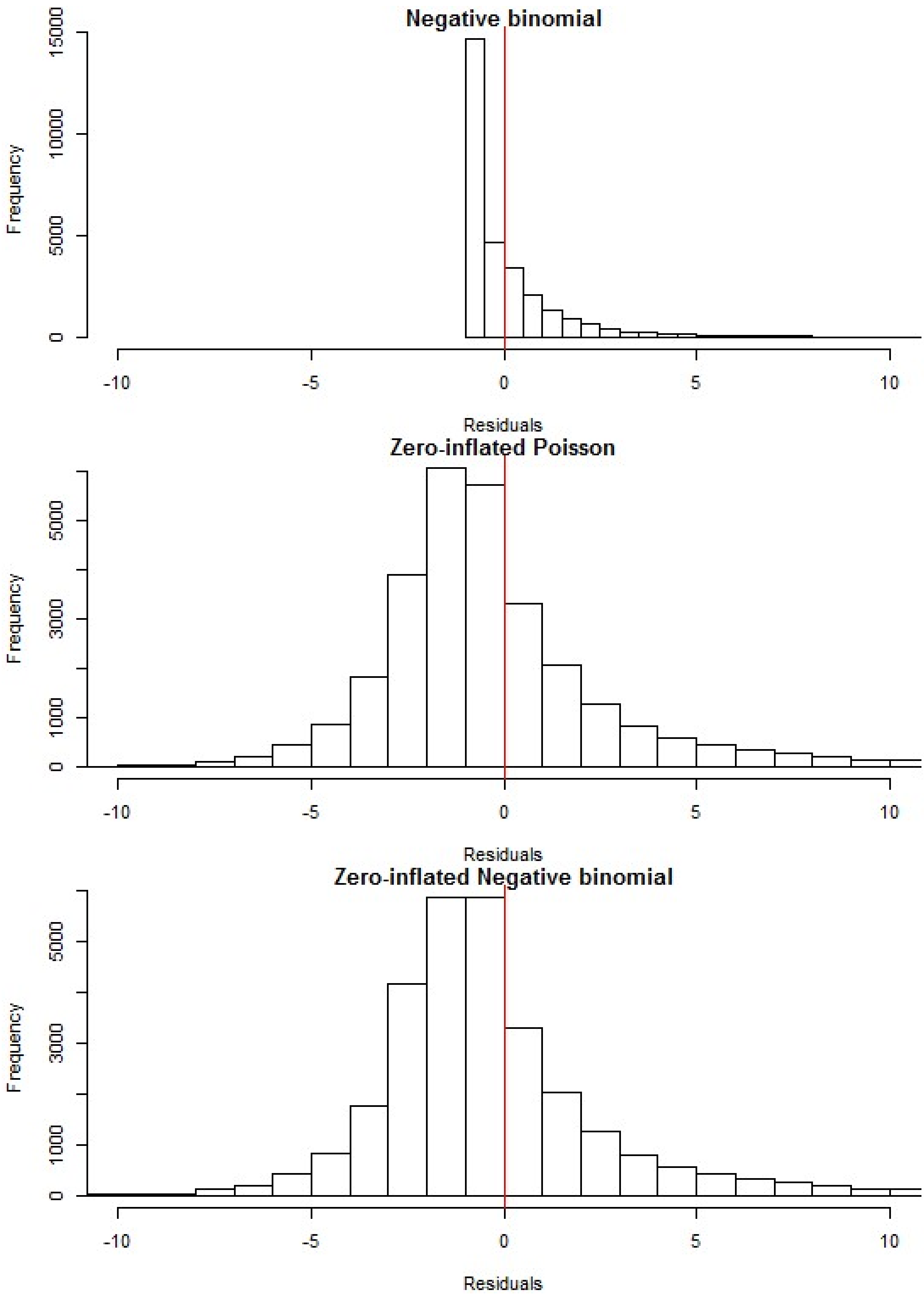


Fig. 9 Histograms of Pearson residuals for CPUE values under the Negative Binomial (NB), Zero-Inflated Poisson (ZIP), and Zero-Inflated Negative Binomial (ZINB).

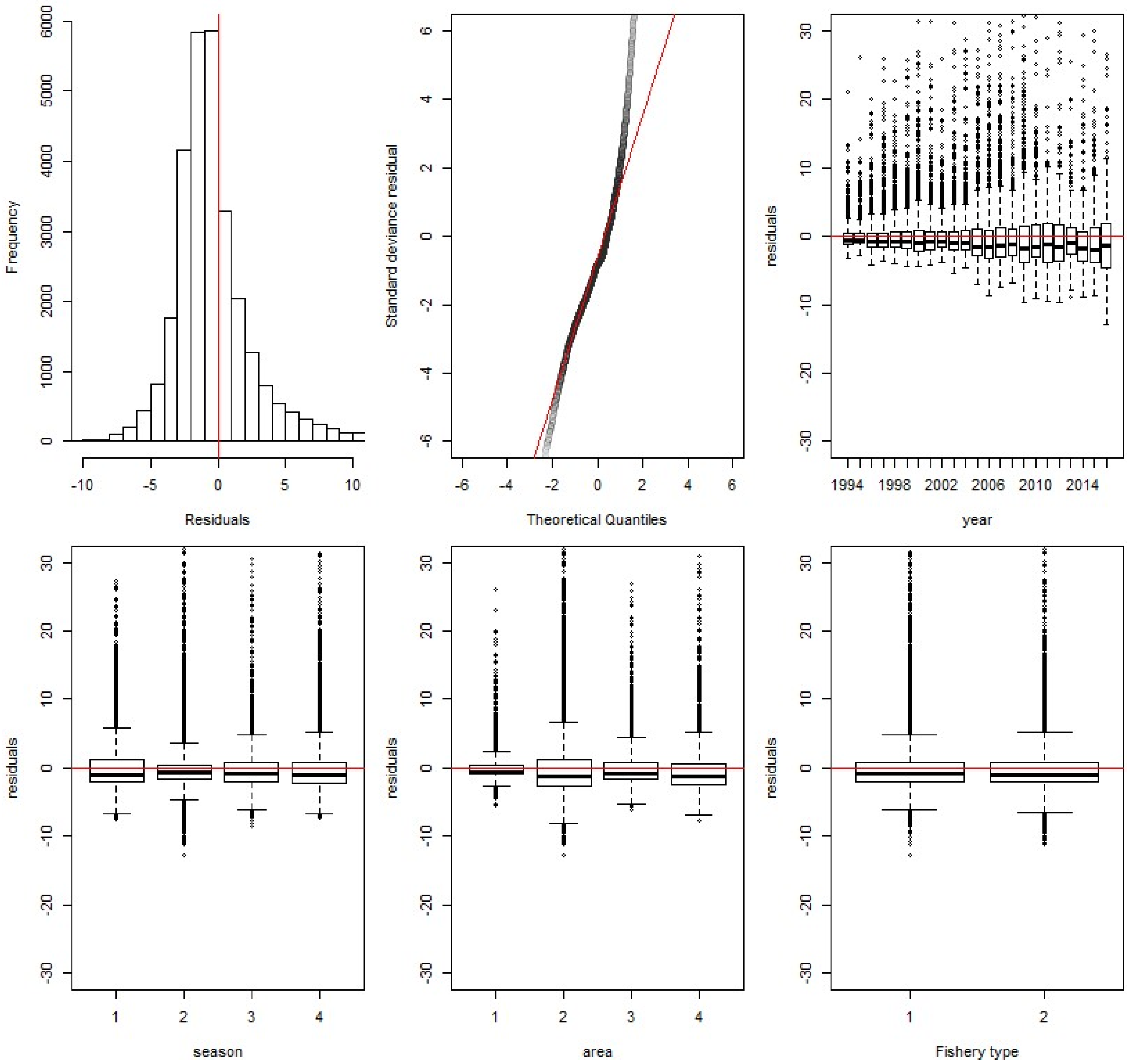


Fig. 10 Pearson residuals for CPUE values, Q-Q plot, and box plots of Pearson residuals against each explanatory variable from Zero-Inflated Negative Binomial (ZINB). Numerical values 1 and 2 of "fishery type" denotes "offshore" and "distant water", respectively.

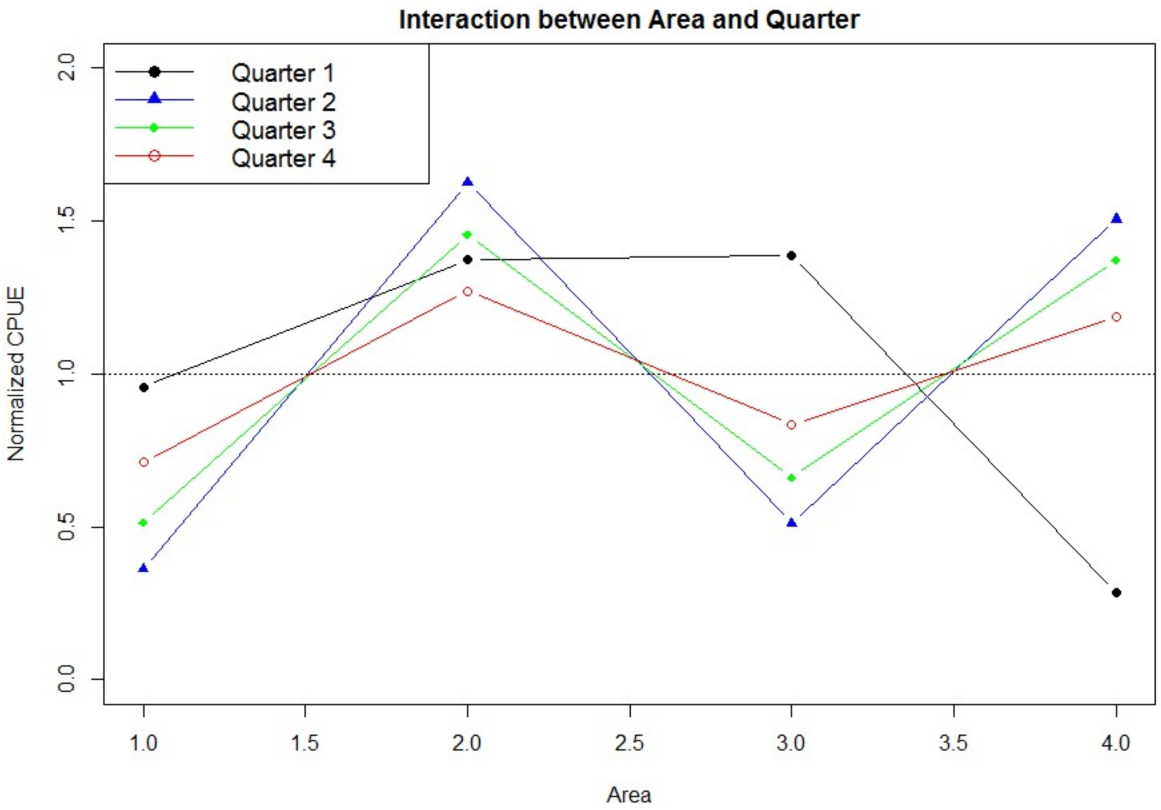


Fig. 11 Relationships of standardized CPUE between area and quarter. Horizontal dotted line denotes a mean value of area for each quarter.

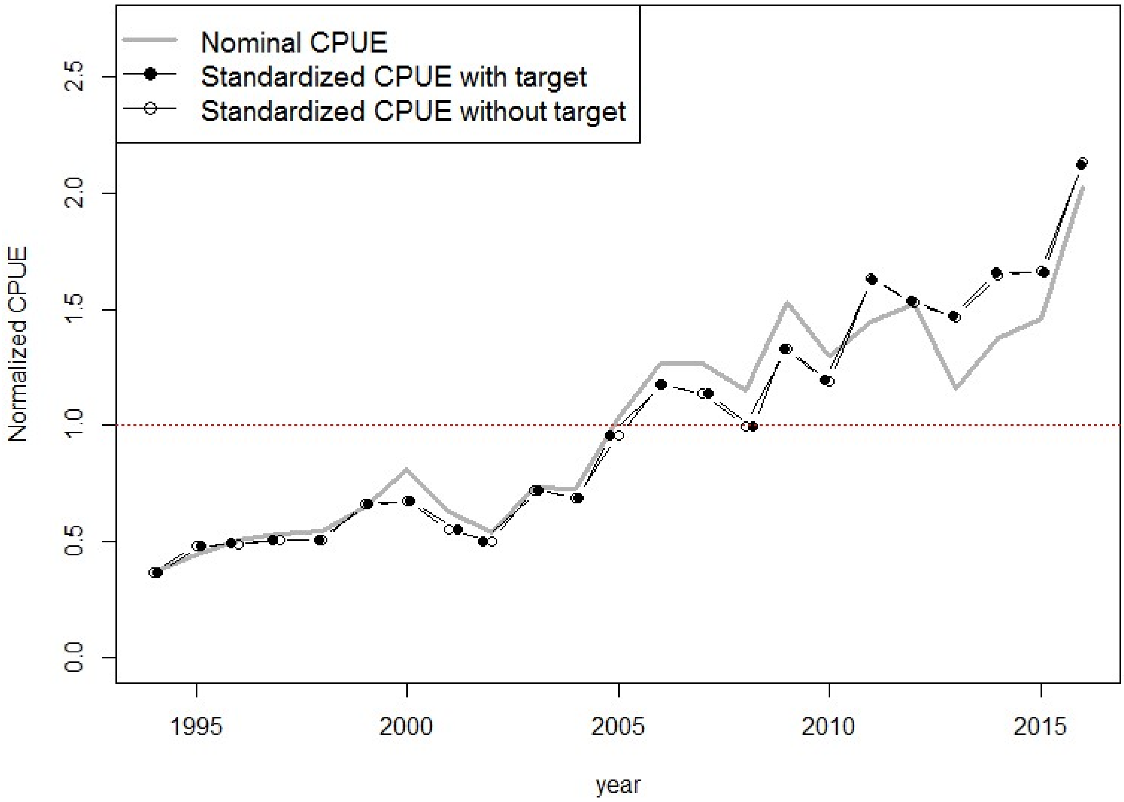


Fig. 12 Yearly changes in nominal and standardized CPUE estimated from Zero-inflated Negative Binomial model with and without targeting effect. Horizontal dotted line denotes a mean value of each time series.

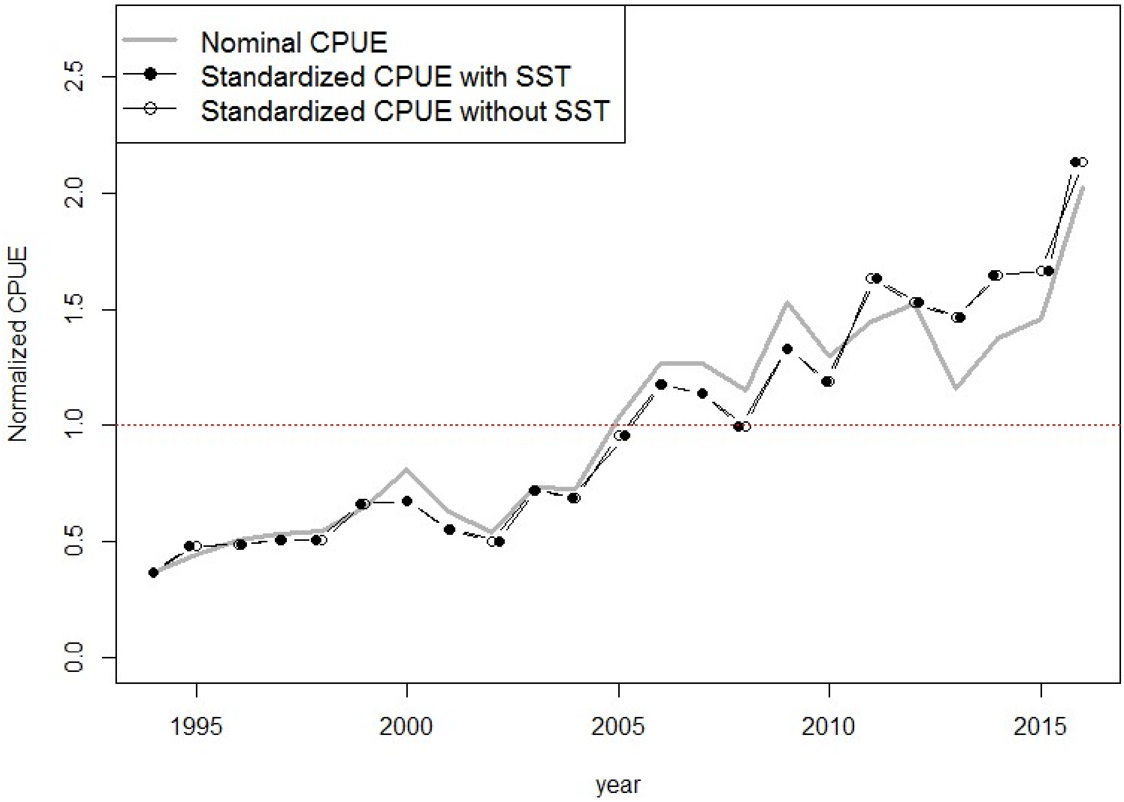


Fig. 13 Yearly changes in nominal and standardized CPUE estimated from Zero-inflated Negative Binomial model with and without effect of SST. Horizontal dotted line denotes a mean value of each time series.

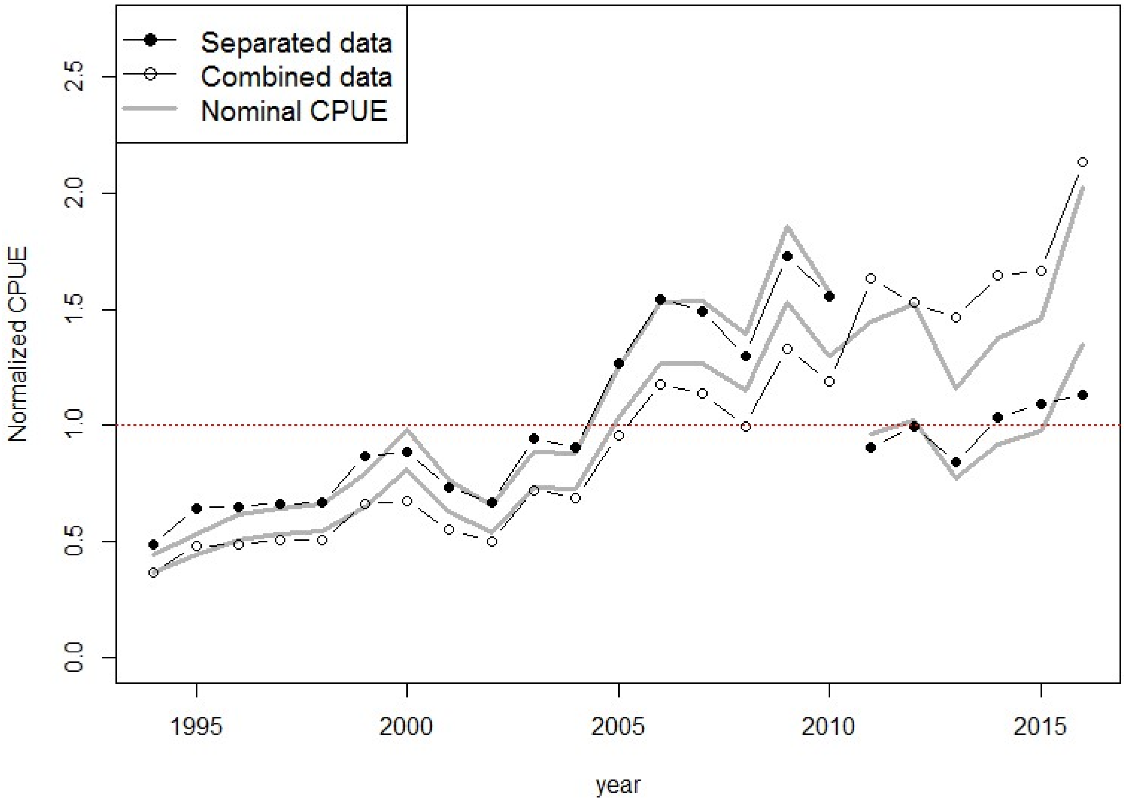


Fig. 14 Yearly changes in nominal and standardized CPUE estimated from Zero-inflated Negative Binomial model for separated and combined data. Horizontal dotted line denotes a mean value of each time series.

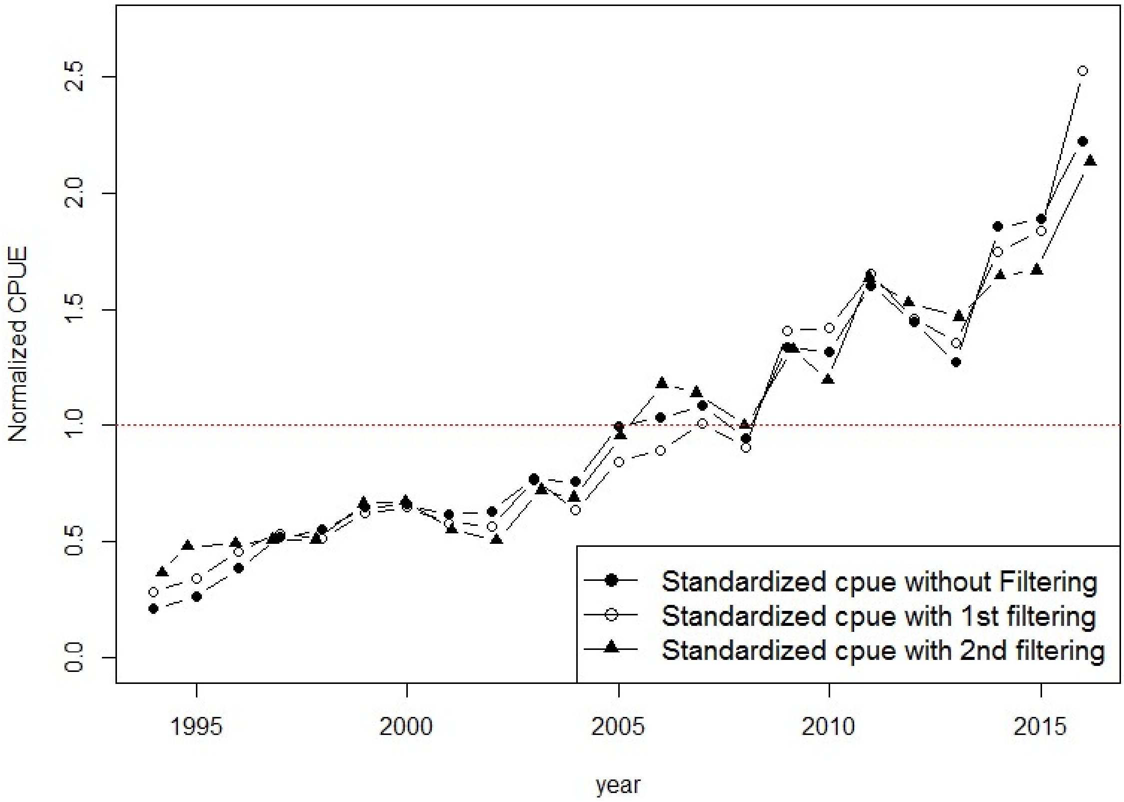


Fig. 15 Yearly changes in standardized CPUE estimated from Zero-inflated Negative Binomial model for data with and without filtering. Horizontal dotted line denotes a mean value of each time series.

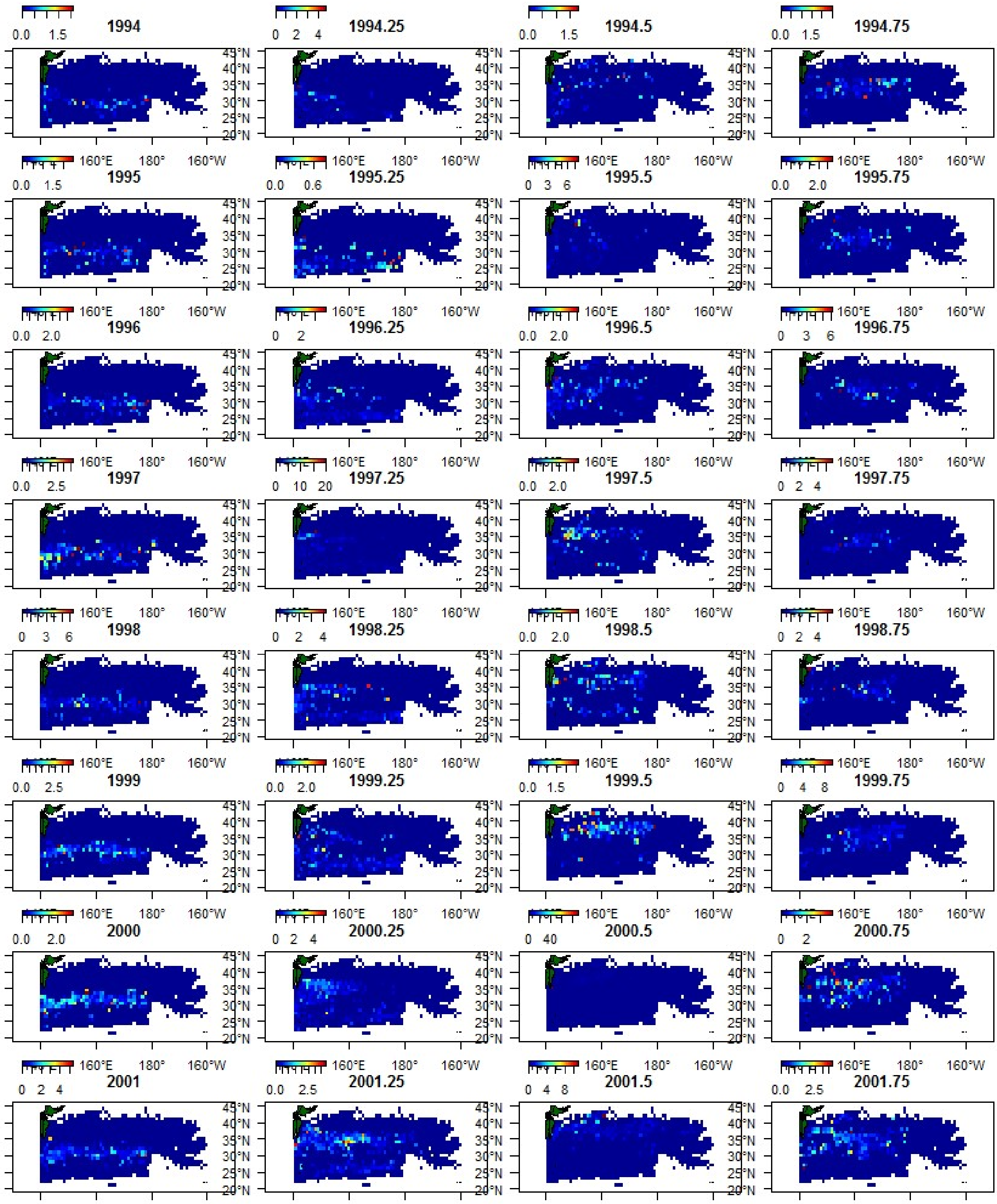


Fig. 16 Catch location of shortfin mako shark in the North Pacific from 1994 to 2001 by season. Each column denotes season1, season2, season3, and season4, respectively from left to right.

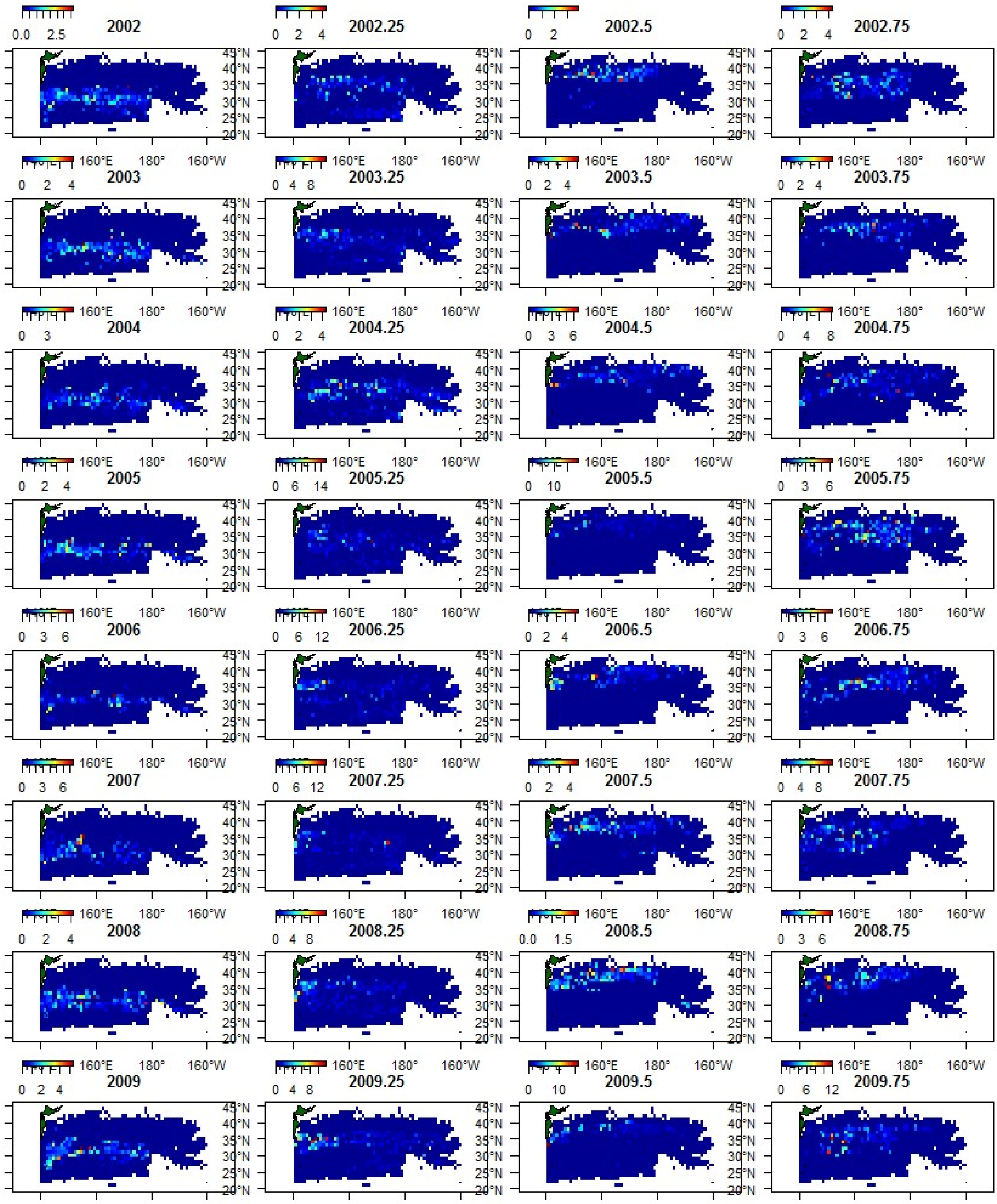


Fig. 17 Catch location of shortfin mako shark in the North Pacific from 2002 to 2009.

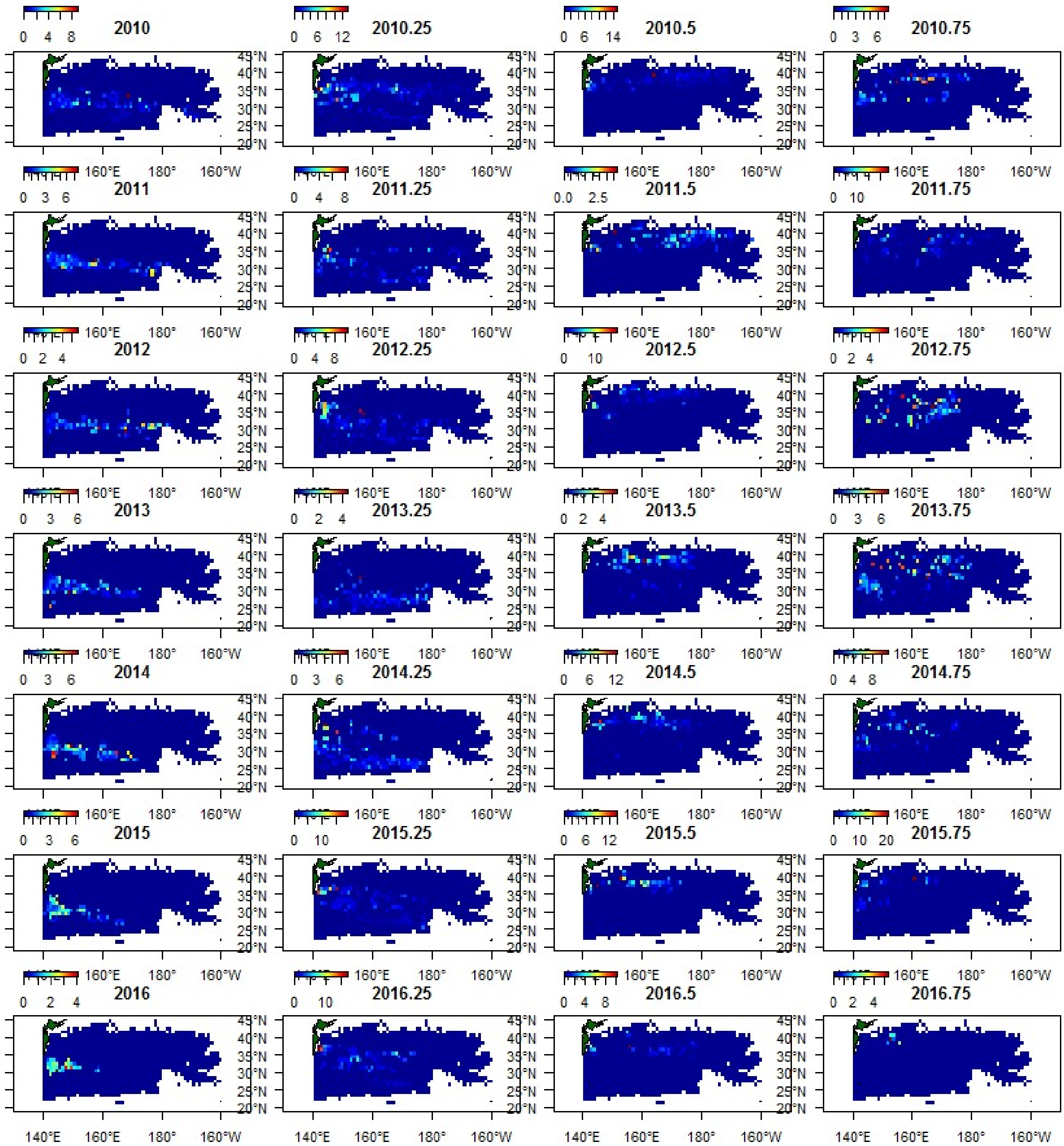

Fig. 18 Catch location of shortfin mako shark in the North Pacific from 2010 to 2016.

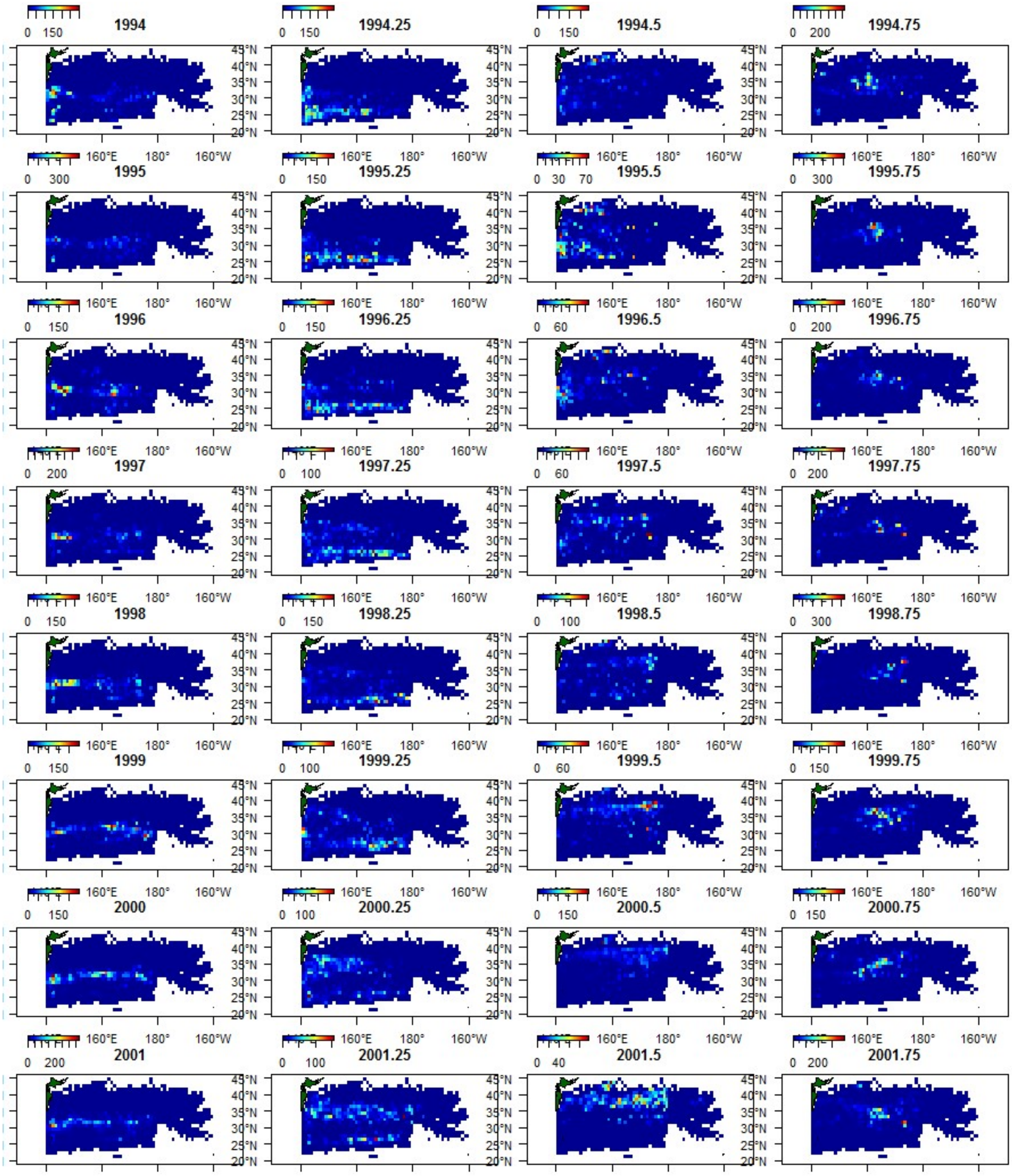


Fig. 19 Operational locations of shallow-set longline and fishing effort (number of hooks x 1000) in the North Pacific from 1994 to 2001.

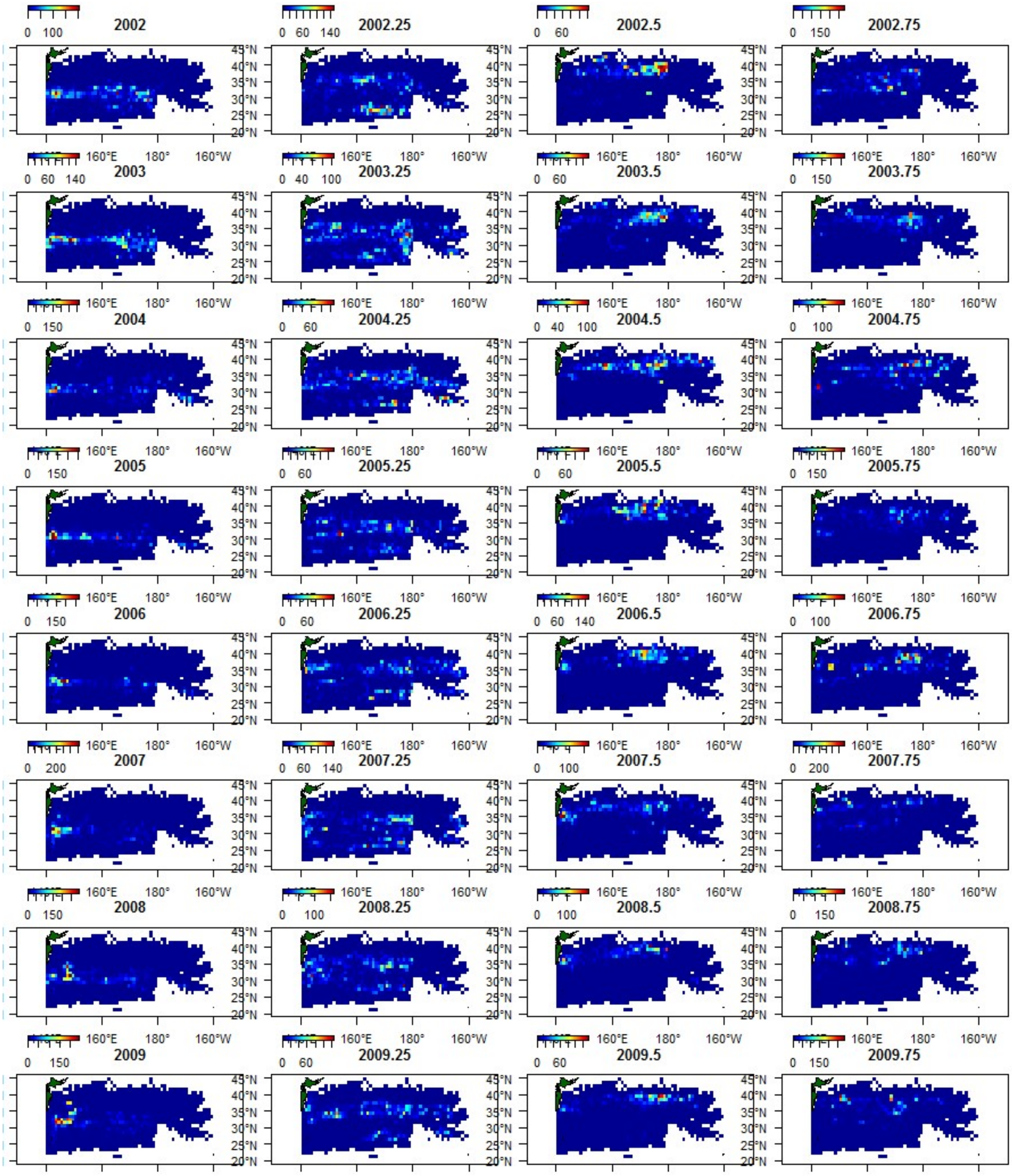

Fig. 20 Operational locations of shallow-set longline and fishing effort (number of hooks x 1000) in the North Pacific from 2002 to 2009.

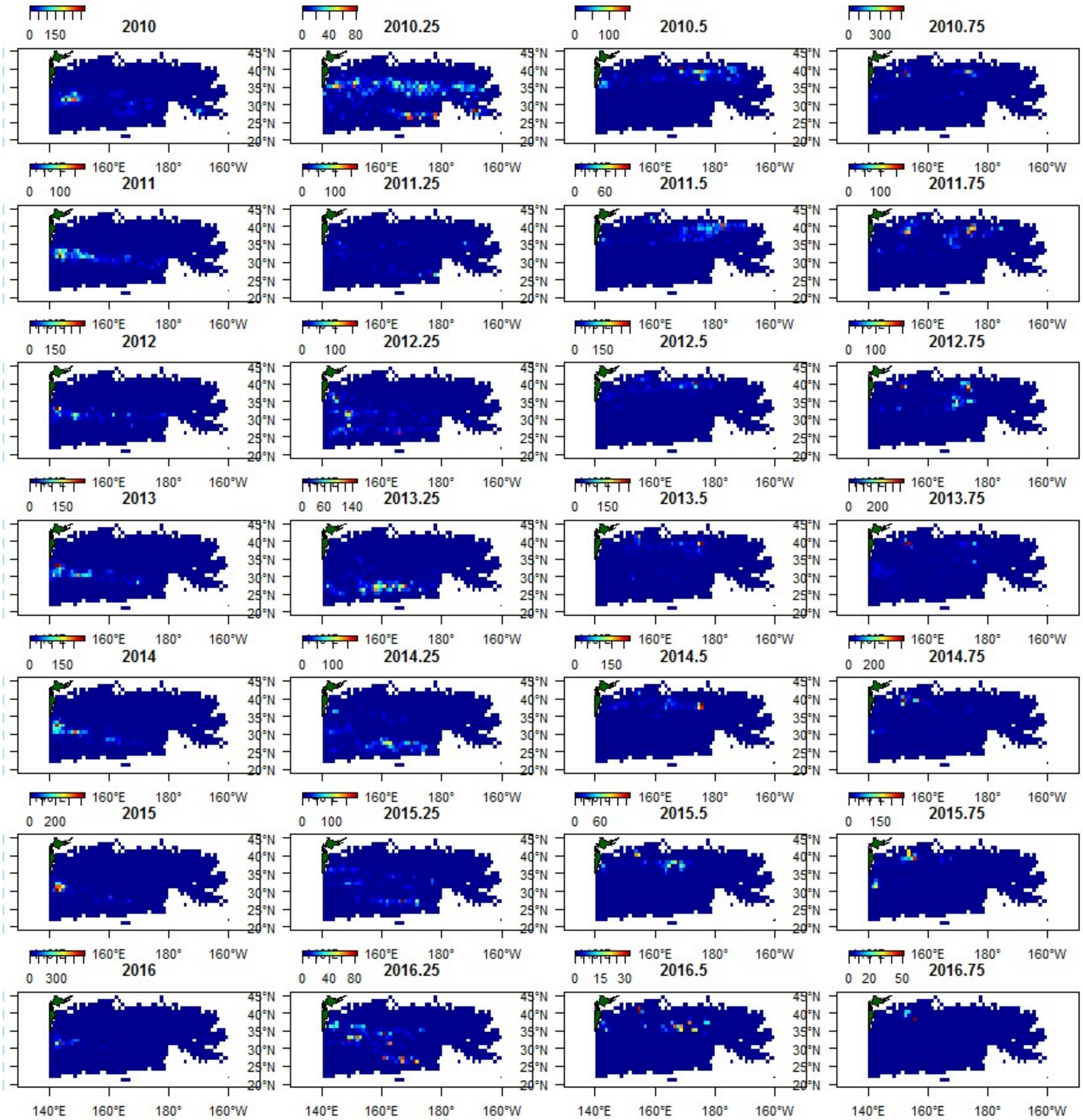


Fig. 21 Operational locations of shallow-set longline and fishing effort (number of hooks x 1000) in the North Pacific from 2010 to 2016.

Summary of base-case output for zero-inflated negative binomial model

```
Call:
zeroinfl(formula = mako ~ factor(year) + factor(qt) + factor(area) + factor(fishery) +
   factor(area):factor(qt) + offset(log(hook)) | factor(year) + factor(qt) +
    factor(area) + factor(fishery), data = tempb, dist = "negbin")

Count model coefficients (negbin with log link):
                    Estimate Std. Error  z value Pr(>|z|)
(Intercept)         -7.95547    0.05790 -137.393  < 2e-16 ***
factor(year)1995     0.11088    0.06264    1.770  0.07671 .
factor(year)1996     0.34743    0.06105    5.691 1.26e-08 ***
factor(year)1997     0.46734    0.06191    7.549 4.38e-14 ***
factor(year)1998     0.42465    0.05995    7.084 1.40e-12 ***
factor(year)1999     0.36808    0.05672    6.489 8.62e-11 ***
factor(year)2000     0.46534    0.05674    8.201 2.38e-16 ***
factor(year)2001     0.38188    0.06024    6.340 2.30e-10 ***
factor(year)2002     0.30361    0.06016    5.047 4.49e-07 ***
factor(year)2003     0.76058    0.06155   12.358  < 2e-16 ***
factor(year)2004     0.55343    0.06089    9.088  < 2e-16 ***
factor(year)2005     0.93049    0.06191   15.029  < 2e-16 ***
factor(year)2006     0.94369    0.06012   15.698  < 2e-16 ***
factor(year)2007     0.98016    0.05860   16.727  < 2e-16 ***
factor(year)2008     0.77983    0.06000   12.998  < 2e-16 ***
factor(year)2009     1.17541    0.06294   18.676  < 2e-16 ***
factor(year)2010     1.06428    0.06730   15.814  < 2e-16 ***
factor(year)2011     1.34168    0.07709   17.405  < 2e-16 ***
factor(year)2012     1.25854    0.07473   16.842  < 2e-16 ***
factor(year)2013     1.23884    0.07661   16.170  < 2e-16 ***
factor(year)2014     1.37430    0.08666   15.859  < 2e-16 ***
factor(year)2015     1.41574    0.08479   16.696  < 2e-16 ***
factor(year)2016     1.53993    0.08367   18.404  < 2e-16 ***
factor(qt)2         -0.72475    0.03899  -18.590  < 2e-16 ***
factor(qt)3         -0.57233    0.09219   -6.208 5.35e-10 ***
```

```
factor(qt)4              -0.03877    0.15146   -0.256  0.79797
factor(area)2             0.36093    0.03850    9.375  < 2e-16 ***
factor(area)3             0.36936    0.05614    6.579 4.74e-11 ***
factor(area)4            -1.21621    0.83379   -1.459  0.14466
factor(fishery)2         -0.18880    0.02179   -8.665  < 2e-16 ***
factor(qt)2:factor(area)2  1.14330    0.04842   23.611  < 2e-16 ***
factor(qt)3:factor(area)2  0.68205    0.09876    6.906 4.98e-12 ***
factor(qt)4:factor(area)2  0.21873    0.15424    1.418  0.15616
factor(qt)2:factor(area)3 -0.02485    0.07484   -0.332  0.73986
factor(qt)3:factor(area)3 -0.11645    0.10753   -1.083  0.27882
factor(qt)4:factor(area)3 -0.21174    0.16106   -1.315  0.18862
factor(qt)2:factor(area)4  2.64446    0.86594    3.054  0.00226 **
factor(qt)3:factor(area)4  2.19939    0.83871    2.622  0.00873 **
factor(qt)4:factor(area)4  1.72676    0.84860    2.035  0.04187 *
Log(theta)               -0.13734    0.01749   -7.852 4.10e-15 ***

Zero-inflation model coefficients (binomial with logit link):
                 Estimate Std. Error z value Pr(>|z|)
(Intercept)       -5.9437     5.7894  -1.027 0.304583
factor(year)1995  -1.8158     0.6864  -2.645 0.008158 **
factor(year)1996   0.3493     0.2923   1.195 0.232034
factor(year)1997   0.8434     0.2710   3.112 0.001855 **
factor(year)1998   0.6232     0.2662   2.341 0.019246 *
factor(year)1999 -10.3604    63.0639  -0.164 0.869508
factor(year)2000  -1.5669     0.4323  -3.625 0.000289 ***
factor(year)2001  -0.2417     0.3025  -0.799 0.424289
factor(year)2002  -0.1524     0.3056  -0.499 0.618067
factor(year)2003   0.5218     0.2730   1.912 0.055932 .
factor(year)2004  -0.7120     0.3800  -1.874 0.060999 .
factor(year)2005  -0.2617     0.3062  -0.855 0.392642
factor(year)2006 -12.1361    65.9209  -0.184 0.853935
factor(year)2007  -1.7461     0.3363  -5.191 2.09e-07 ***
factor(year)2008 -14.0857   104.8049  -0.134 0.893087
factor(year)2009  -1.1202     0.3107  -3.605 0.000312 ***
```

```
factor(year)2010  -1.1488     0.3299  -3.482 0.000498 ***
factor(year)2011  -1.7121     0.4347  -3.939 8.20e-05 ***
factor(year)2012  -2.0383     0.4354  -4.682 2.84e-06 ***
factor(year)2013  -1.6206     0.3718  -4.358 1.31e-05 ***
factor(year)2014  -1.3110     0.3517  -3.728 0.000193 ***
factor(year)2015  -0.9455     0.3178  -2.975 0.002928 **
factor(year)2016 -13.2039   225.2360  -0.059 0.953253
factor(qt)2       -0.3768     0.2098  -1.797 0.072413 .
factor(qt)3       -1.4758     0.2302  -6.412 1.43e-10 ***
factor(qt)4        0.6624     0.1359   4.874 1.09e-06 ***
factor(area)2      3.8398     5.7424   0.669 0.503701
factor(area)3      3.7871     5.7439   0.659 0.509690
factor(area)4      6.1883     5.7445   1.077 0.281364
factor(fishery)2   0.5697     0.1139   5.001 5.71e-07 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Theta = 0.8717
Number of iterations in BFGS optimization: 94
Log-likelihood: -5.869e+04 on 70 Df
```